Magnetic Noise Associated with Ocean Internal Waves

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***Abstract-* Environmental noise can be a major limitation on the performance of magnetic sensor systems in continental shelf regions. Previous work has predicted the magnetic influence from internal waves and indicates that these could be important components of ambient ocean magnetic noise. Existing electric and magnetic field sensor technology has an instrument noise floor well below the ambient magnetic noise in shallow water applications. Model predictions indicate that internal oceanographic features, such as high amplitude internal waves, internal bores and solitary waves, can contribute magnetic variations in the very low frequency band ranging from 0.1 to 1.0 nT which is well above the noise level of commercial magnetometer systems. Predictions of the magnetic character for internal ocean dynamics are computed using a nested non-hydrostatic ocean model coupled with a simple electromagnetic model. These predictions should correlate with oceanographic observations of water velocity. Comparison of the model predictions with observed oceanographic measurements is under investigation.**

I. Introduction

An important source of extremely low frequency electromagnetic (EM) variations in the ocean is caused by the motion of the electrically conductive water through the earth's magnetic field. Movement of sea water in the earth's magnetic field produces an electromotive force with an associated electric current and magnetic field. As a result, surface waves, internal waves, solitary waves, tides, and ocean currents all produce observable magnetic and electric fields. These ocean dynamics contribute to the magnetic field that magnetic sensors observe when measuring the field over ocean areas. As a result, the ocean dynamics appear as variable magnetic anomalies that change on the scale of the ocean features they represent. For stationary magnetic sensors like those deployed on the bottom, the ocean dynamics should appear as periods of increased magnetic background noise. For airborne magnetic sensors traveling across a segment of ocean, the ocean dynamics should appear as non-stationary anomalies that move or change with time.

Early studies of magnetic and electric fields generated by ocean flow [1] were concerned with electric fields induced by the steady motion of seawater. Internal waves have been observed with magnetic sensors in the deep ocean and are routinely characterized by measuring the electric and thermal structure using in-water sensors. Theoretical models for internal wave induced magnetic spectra indicate that the amplitude increases with decreasing frequency, and predictions of the influence on magnetic surveys have been calculated based on these models. Beal and Weaver [2] developed a model for the induced magnetic field from internal waves in a two-layered ocean. Podney [3] followed with a more comprehensive treatment of internal waves for an exponentially stratified ocean with a horizontally uniform Brunt-Vaisala frequency profile. Later on Petersen and Poehls [4] used Podney's formulation combined with the Garrett and Munk [5] model of internal wave spectra to generate a spectral estimate of the magnetic induction. Chave [6] derived a somewhat more general solution for internal waves that also used the Garrett and Munk wave spectra and presented predictions of the magnetic power spectra above and below the water surface.

For the purposes of this paper, we will focus on the magnetic fields produced by internal ocean dynamics in the frequency band from 0.1 to 0.0001 Hz and present some initial magnetic observations to characterize the magnetic fields associated with internal waves. Theoretical models for internal wave induced magnetic spectra indicate that the amplitude increases with decreasing frequency most likely related to longer wavelength features. Previous model analysis [7] demonstrated that ocean dynamics could impact airborne magnetic measurements and showed that model predictions agreed with published analytic predictions. These model predictions were computed with a high resolution non-hydrostatic ocean model hindcast of the mesoscale and submesoscale circulation within a region off the coast of New Jersey in the same area as the experiment described by this paper.

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These forward model predictions verified that ocean dynamics should create observable magnetic fields and supported the experiment design used to acquire the data presented here.

II. Experiment and Data Analysis

During the summer of 2009 a series of measurements were taken with the objective to measure and characterize the observable magnetic field of ocean dynamics and to compare these observations with model predictions. The measurement area was seaward of the New Jersey coast where a number of previous oceanographic and geologic studies have taken place. Recorded data included moored and towed oceanographic measurements to characterize the ocean dynamics plus undersea magnetic measurements, and airborne magnetic measurements. Fig. 1 shows the experiment area with the airborne magnetic measurement flight line and approximate locations of the moored oceanographic and magnetic sensors. A research ship, OCEANUS, conducted instrumented tows to characterize the ocean dynamics in concert with the moored measurements along a profile line parallel (but slightly offset) to the flight line.

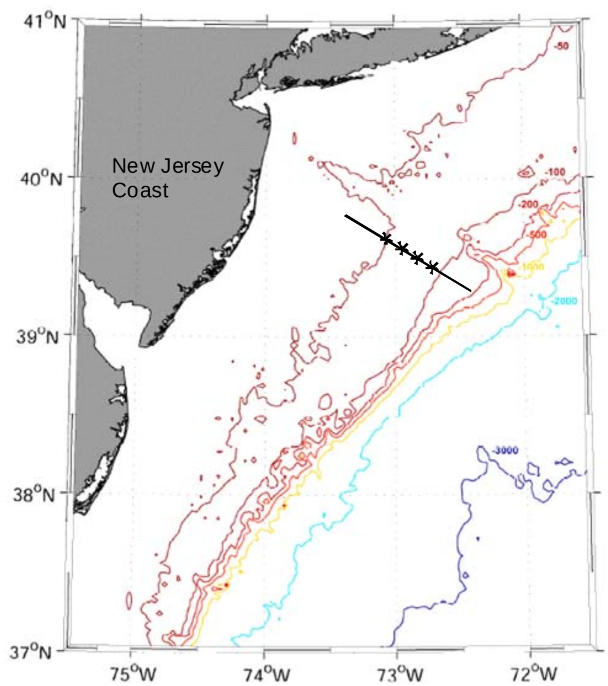

Fig. 1 Experiment area off the New Jersey coast showing undersea oceanographic and magnetic sensor locations with asterisk and the airborne magnetic measurement flight line.

The primary ocean instrumentation was located in 60-100 meters of water across the shelf in a profile perpendicular to the shelf slope. Site selection and instrument spacing were based on available data from previous research, and an oceanographic instrument spacing of five kilometers was selected to optimize measurement spacing for the anticipated oceanography. The ocean dynamics were characterized using four barny Acoustic Doppler Current Profiler (ADCP) moorings, two string conductivity-temperature moorings, and numerous scanfish tows throughout the cruise period. These data produced a high spatial and temporal density of ocean measurements to characterize the fluid flow and temperature-salinity properties of the ocean during the test.

The undersea magnetic measurements are from four bottom deployed magnetic systems. To record data during the entire week of oceanographic measurements, two sets of four magnetic systems were deployed for a battery life of three days each. These systems are co-located and offset by about 200 meters relative to the four barny ADCP systems. Each magnetometer system consisted of an Overhauser magnetic sensor that measures the scalar (Total) magnetic field of the earth. The systems recorded data samples at three second intervals to optimize the data acquisition and battery life of the units. This results in a Nyquist frequency of 0.1667 Hz which was determined to be adequate for the experiment. Each grouping of four units performed well and recorded approximately three days of uninterrupted measurements after deployment with only one magnetic sensor from the second grouping failing to record the full suite of data.

Preliminary data processing for the undersea magnetic systems focused on time coherence of the system samples and removal of the coherent temporal variations associated with ionospheric variability. The residual from this coherent signature processing is the time varying magnetic signature of the ocean dynamics plus any residual instrument noise. The noise floor for this type magnetic sensor is approximately 0.05 nT/√Hz and is more than adequate to observe the ocean dynamics. An amplitude spectral estimate is computed to characterize the magnetic variability from the ocean dynamics.

Data segments of 6000 seconds long are computed into sequential amplitude spectral estimates for the entire three days of data. These are compiled into a time evolution of the spectral character of the data. Fig. 2 shows the amplitude spectral character from site A4 on the deeper end of the line in 92 meters water. Variations in Fig. 2 from 0.0002 Hz to approximately 0.01 Hz represent the ocean dynamics observed by this sensor and this plot is typical of the other three sites along the line. The scale on the plot is in dB relative to 1 nT/√Hz. Multiple periods are observable that represent larger episodes of higher ocean dynamic activity. These higher activity periods most likely correspond to packets of internal waves passing the sensor at A4. Amplitudes at 0.001 Hz can exceed +10 dB during some of these periods. One event at approximately 4000 minutes extends significant variability into frequencies higher than 0.01 Hz.

The airborne magnetic data were recorded with two aircraft, the Naval Research Laboratory P-3 aircraft and the National Research Council of Canada Convair aircraft. Both aircraft recorded data simultaneously so that special data processing techniques could be used to remove noise and isolate magnetic effects of ocean dynamics. The aircraft data are recorded along the same profile from as many as 50 or more repeated flights to build up a comprehensive geologic model of the magnetic character along the flight path. Data from the aircraft were processed with both time domain and frequency domain techniques to determine the optimal procedure for these data.

Data processing included advanced noise removal techniques to remove noise generated by aircraft motion, motion of the sensor in the gradient of the earths' magnetic field, changes in geology along the flight path, and temporal variations of the earth's magnetic field due to ionospheric currents. Frequency domain noise reduction processing seemed to work the best and produced the lowest noise residuals. A final display for eight flight lines with each line offset vertically for clarity is shown in Fig. 3. Each line is recorded along the same flight profile such that variations between the profiles should reveal changes due to external factors like ocean dynamics. The oval line in Fig. 3 highlights an anomalous segment that fits the concept for how ocean dynamics should appear in the data. Further analysis and comparison with the oceanographic data will be required to confirm the relationship to ocean dynamics. However, these results point to the impact that ocean dynamics can have on magnetic surveys and undersea measurements.

III. Summary

Previous work in the literature suggested that magnetic fields generated by ocean dynamics should affect magnetic measurement systems and should be considered in surveys or measurement design. Experimental data recorded in June 2009 off the coast of New Jersey appear to confirm that magnetic fields generated by ocean dynamics could produce a significant contribution to noise in airborne and undersea measurement systems.

Acknowledgment

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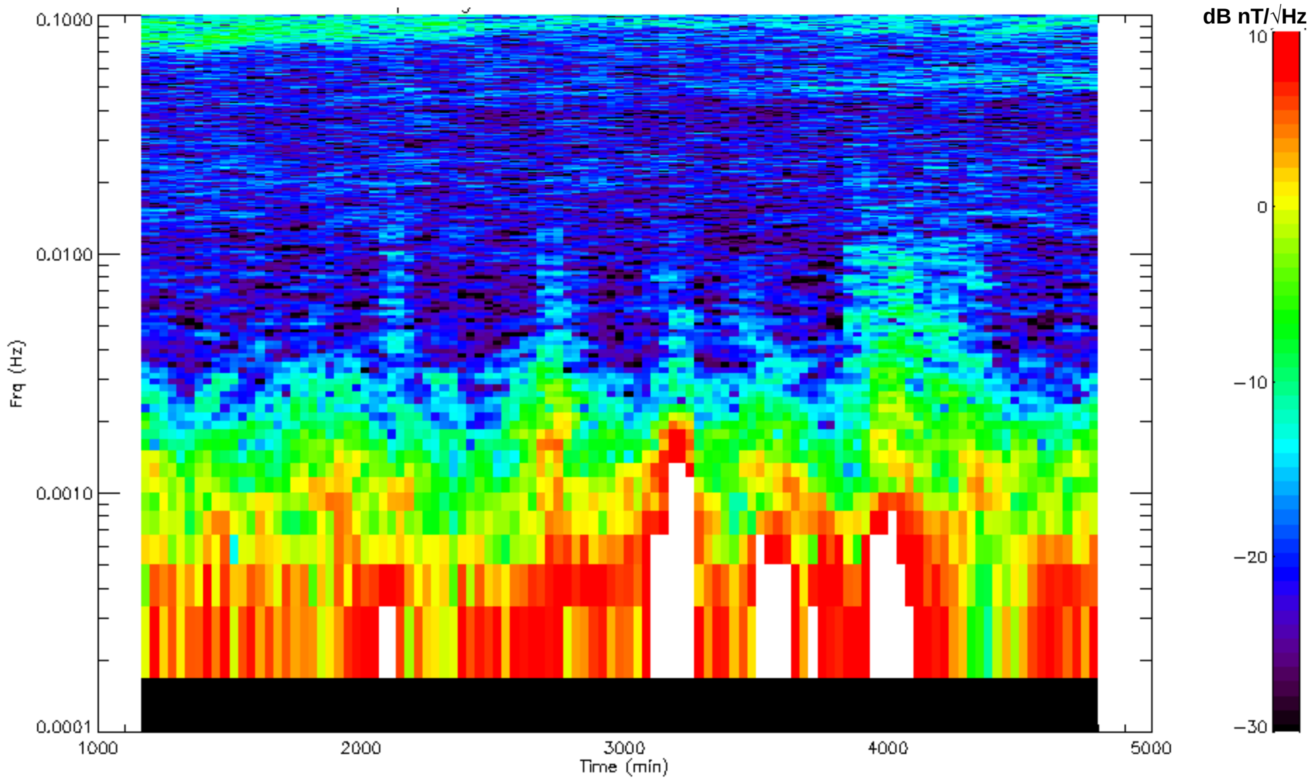

Fig 2. Amplitude spectral plot from a representative undersea magnetic sensor showing internal ocean dynamics after ionospheric variations are removed. The plot shows the time evolution of the magnetic amplitude spectra vs frequency.

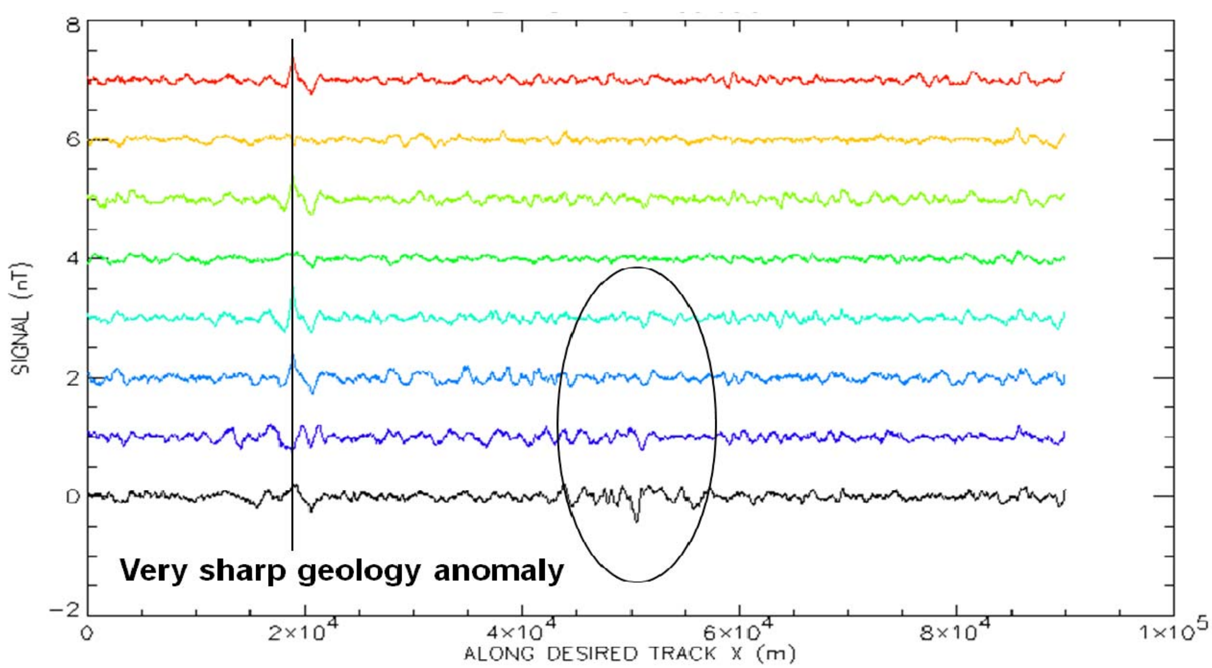

Fig 3. A group of airborne tracks (offset for visual clarity) along the experiment line showing variations over the time evolution of each track. Tracks are roughly 15 minutes apart. The variations highlighted by the oval are variations that change with time as would be expected from ocean dynamics. The sharp variation at $2x10^4$ meters is most likely a residual geologic anomaly.